AN EXPERIMENTAL LASER RANGING SYSTEM

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Summary

An experimental ranging system has been constructed utilizing the ruby laser of T. H. Maiman. When excited by a xenon flash tube the ruby laser emits a pulse of red light (6943Å) of high spectral purity. The beam emanating from the laser is already quite well collimated. With the addition of a telescope an extremely narrow beam of 0.4 milliradians is obtained. This light is reflected from a target and the return signal collected on a photomultiplier by means of another telescope. Spectral filtering provides discrimination against unwanted optical signals. Both transmitted and reflected signals are displayed on a dual beam oscilloscope and range is calculated from the displacement of the traces.

Ranging was successfully accomplished at 3000 meters in broad daylight and at 11,200 meters at night. Calculations have been made to establish limiting factors and to indicate ways of improving performance.

Introduction

Among the many potential applications of the solid state laser, a ranging system appears to be one of the most promising. In order to exploit the achievement of an operating laser[1,2] in this direction, an effort was undertaken to build an experimental ranging system (radar) utilizing a ruby laser, together with components and techniques which were readily available. In addition, the question has also been studied, what can be done with lasers and auxiliary components specifically developed and matched for this application? The purpose of this paper is to report on the achievement of a rudimentary ranging device with a minimum developmental effort and to indicate briefly the theoretical examination of the possibilities and limitations of more sophisticated and better designed systems. The first part of this paper is devoted to the description of the system as it was actually built and tested; this is then followed by a resume of the performance data and finally by discussions of theoretical and speculative nature concerning laser ranging systems to be built in the future.

Organization of the System

The transmitter of the laser ranging system is a ruby crystal with linear dimensions of the order of an inch. The ruby is driven by a pulse of white light from a xenon flash tube. The crystal itself acts as a highly directive radiator. Aiming of the beam is accomplished by orienting the crystal in the proper direction. When the natural collimation of the laser beam is inadequate, a lens system or telescope is added to decrease the beamwidth.

Light reflected from the target is gathered by a telescope and then detected by a photomultiplier tube, which converts the light into an electrical signal. This signal is then displayed on the screen of an oscilloscope which also displays a sample of the transmitted signal. Range is determined from the displacement of the received signal with respect to the transmitted one. A block diagram of the system is given in Fig. 1. In addition to the elements shown in Fig. 1, there is an optical filter incorporated in the telescope. The

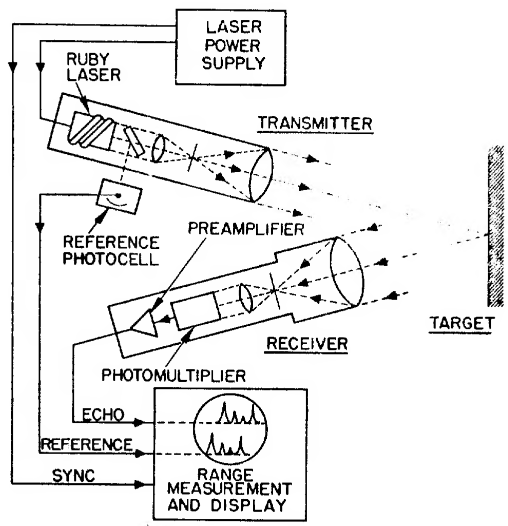

Fig. 1. Block diagram of system.

purpose of the filter is to provide discrimination against light not originating in the laser. This is essential in order to exploit one of the principal features of the laser, the concentration of energy in a very narrow spectral region.

The Components

The key element of the system is the ruby laser whose principal characteristics are tabulated below.

Laser Characteristics

Energy input per pulse	1200 joules
Peak optical power output	300-2000 watts
Frequency, f	4.321×10^{14} cps
Wavelength, λ	6943×10^{-8} cm
Wavelength band $\Delta\lambda$	$< 0.1 \times 10^{-8}$ cm
Width of radiated beam:	
Laser alone	12 milliradians (0.7°)
With telescope	0.4 milliradians (1.4')

Fig. 2 is a photograph of the laser which was constructed for this experiment by T. Maiman, who was responsible for the first operating ruby laser.[1] The crystal is surrounded by a xenon flash tube

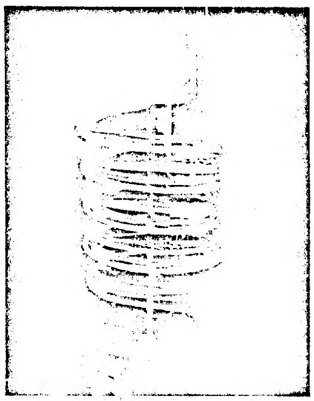

Fig. 2. Ruby laser.

capable of generating an intense flash of essentially white light. The flash is produced by discharging a capacitor bank of 2000 μf charged to about 1350 volts; it lasts about 1 msec. The emission of coherent radiation from the ruby begins a few hundred microseconds after the onset of the flash. The intensity of the emitted light is a very irregular function of time as shown in Fig. 3. Optical power output was measured with a diode-connected 6217 photomultiplier which had been calibrated by comparison, at 6943 Å, with a standard thermopile.

Ideal lasers should eventually provide extremely well collimated output beams ($\sim 10^{-5}$ radians). Because the beamwidth of the ruby laser used here is 12 milliradians, most of the experiments were conducted with a 6-inch reflecting telescope which provides an angular demagnification factor of 34. The 0.4 milliradian beamwidth

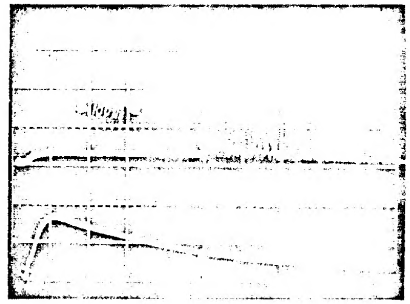

Fig. 3. Laser output. The upper trace gives laser output intensity versus time; th lower trace shows the output of the pumping xenon flash lamp.

of the system was measured by observing the diameter of the spot (7 ft) at 3.4 miles.

A time reference for range measuremer is established by sampling the laser output. Tl is accomplished by the use of a partially reflec glass plate and a photocell with red Wratten and neutral density filters.

Light is gathered in the receiver by a re atively large aperture telescope (5-inch diamet area of aperture = 0.0126 m^2, f/2.5). The ligl is filtered and then directed onto the cathode of the photomultiplier. In order to obtain good dis crimination against noise, a narrow band optica filter must be used. This requires an interfere filter which has certain peculiarities which infl ence the design of the telescope optics. Interfe ence filters must be operated near normal incidence; the rays must be nearly parallel at the pla of the insertion of the filter. Moreover, the av able interference filters are relatively small in area. Finally, while their passband is narrow, interference filters provide only about 30 db dis crimination against unwanted radiation. It is shown in Fig. 4 that a combination of two lense is used to reduce the cross section of the beam light without changing the parallelism of the ray and the interference filter is inserted in the nar row beam. To enhance rejection of light in cer tain undesirable spectral regions beyond the 30-capability of the interference filter, a broadban Wratten filter is also inserted. It is placed in t region where the rays are convergent because tl angle of incidence is not critical in this case. A field stop in the common focal plane of the two lenses serves to limit the solid angle from whic light is permitted to fall on the receiver. This adjustable from 1 to 20 milliradians; a beamwid of 2.5 milliradians (5×10^{-6} steradians) was fre quently employed.

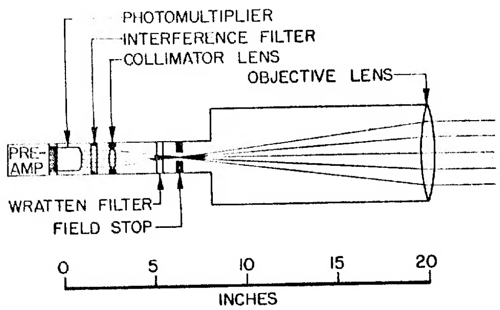

Fig. 4. Photomultiplier receiver.

Conversion of light to electric signal is accomplished by means of an RCA 6217 photomultiplier. As it is seen from Fig. 5, the sensitivity of this tube is still very low for the operating wavelength of 6943 Å. The much higher sensitivity for radiation of higher frequencies is one of the principal reasons for the inadequacy of a 30-db interference filter. Dark current in the photomultiplier consists of spikes in the output occurring at an average rate of 2500 per second. For a receiver operating with a quantum efficiency of 0.01, such an output is equivalent to an input illumination of 7×10^{-12} watt at the wavelength of 6943 Å. This is the noise equivalent power input of the receiver.

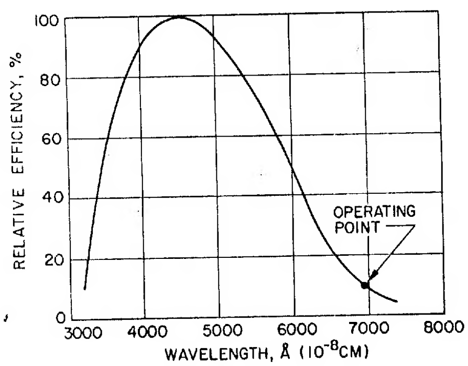

Fig. 5. Response of the RCA 6217 photomultiplier.

Immediately behind the phototube is a preamplifier. Its output is fed into the dual beam oscilloscope which is used as the range measuring instrument. The sweep is triggered simultaneously with the laser output. One of the beams records the sampling of the transmitted signal, the other the signal received. Range is calculated from the displacement of the peaks of the received signal with respect to those of the transmitted one.

The general appearance of the system is shown in Fig. 6.

Fig. 6. Experimental laser ranging system.

Performance

The first significant ranging experiments were conducted in broad daylight against the white stucco wall of a building at 1200 meters (3/4 mile). The lower trace in Fig. 7 shows a sampling of the transmitted signal, the upper trace the return signal. The record contains only a short section of

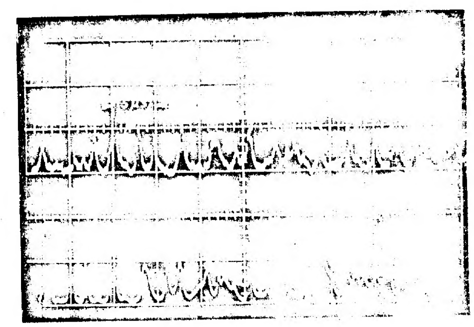

Fig. 7. Ranging return at 1200 meters (3/4 mile) in full sunlight. Note the 8-μsec delay between transmitted (lower) and received (upper) signals.

the burst which lasts of the order of a millisecond. One can easily pick out the peaks of the transmitted signal and note the lateral displacement necessary to bring the peaks into coincidence. This delay corresponds to 8 μsec, from which figure the distance of 1200 meters is readily calculated. To demonstrate the accuracy of the coincidence of the transmitted and received patterns the record shown in Fig. 7 has been cut and the lower part translated to the right by a distance corresponding to 8 μsec. The slightly retouched composite photograph is shown in Fig. 8. Further daytime ranging experiments were conducted against a small rocky bluff 3000 meters away. Although the photographs are not particularly suitable for reproduction the range could be consistently and accurately calculated.

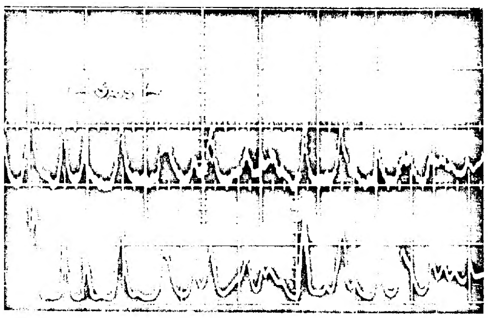

Fig. 8. Fig. 7 translated to bring peaks into coincidence. The photograph has been retouched.

At night a "Scotchlite" white target of 3.0 m^2 geometric cross section was set up at first at 5500 meters (3.4 miles). Tracings were obtained which are readily interpreted and consistent values of the range can be calculated. Similar results were obtained using the side of a garage as a target. The experiments were repeated at night at a distance of 11,200 meters (7 miles); the results were unambiguous and consistent with the distances obtained from maps.

The preceding experiments were performed with the laser at room temperature. When, following a suggestion by R. J. Collins,[3] the laser was cooled by cold nitrogen boiled from the liquid state, significant improvements of the laser output were obtained. With the laser at a temperature of around 210°K, the peak power output increased to about 2000 watts from 600 watts at room temperature. The character of the envelope of oscillations also changed; the onset of radiation became more definite and the large intensity fluctuations were substantially reduced. In this condition, as shown in Fig. 9, the leading edge of the pulse was sufficiently definite to provide range information at night at 7 miles range.

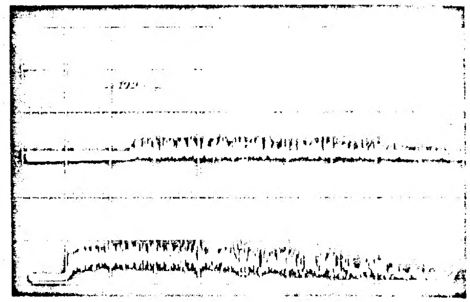

Fig. 9. Ranging return at 11,200 meters (7.0 mile) with cooled laser.

There is no doubt that the performance of laser ranging systems can be further increased even without radical alteration of the scheme described here. These improvements will be discussed in conjunction with the presentation of the theory of the system.

Theory

The principles employed in range calculations for microwave radar are applicable to optical radar as well. The detectability of an object depends on the signal-to-noise ratio at the receiver, and the minimum acceptable value of this ratio is somewhere between one and ten, depending on the pulse repetition rate and on the nature of the information to be derived from the radar data.

The signal returned from an isotropically scattering, completely illuminated target is given by the familiar radar formula

$$S = \frac{PGA_r\sigma}{16\pi^2R^4} , \qquad (1)$$

where P is the power radiated, G the radiator gain, A_r the area of the receiver, σ the equivalent target cross section and R the range. Here we assume that no significant absorption or scattering takes place in the atmosphere so that the attenuation of the signal is solely due to its spreading. With this simplifying assumption the principal difference between the microwave and the optical radar in this respect is the magnitude of the antenna gain which can be achieved conveniently. Diffraction sets a well known limit to the gain in terms of antenna dimensions expressed in wavelength, namely $G < 4\pi A_t/\lambda^2$. While a microwave antenna whose gain is in the thousands is usually sizable; the gain of an optical antenna whose area is comparable to the end of a pencil could be a few hundred millions. For various reasons this high theoretical limit is not achieved in actual lasers. The laser in our experiment had a beamwidth of about 12 milliradians, and this corresponds to a

gain of 110,000; about one hundred times this gain is obtainable from a ruby laser already reported in the literature. With the telescope added in front of our laser we have increased the radiator gain to 100 million which is still short of the ultimate attainable. Thus with the typical values for our system of $P = 10^3$ watts, $\sigma = 2\ m^2$, $A_r = 1.26 \times 10^{-2}\ m^2$, we calculate $S = 1.6 \times 10^{-9}$ watt at a distance of 10^4 meters.

The noise which competes with the signal to be detected originates in part within the receiver, in part on the outside. It is an agreggate of random phenomena which may be classified as follows:

A) Dark current noise. This is the result of random phenomena within the receiver which take place without reference to incident light.

B) External noise. This is the result of the variation in illumination due to other sources of light and the scattering of laser light from objects other than the target.

C) Shot noise. This is the result of random phenomena within the receiver which depend on the total illumination of the receiver.

In order that a proper comparison be made between signal and noise, it is necessary to calculate the input signal intensity which would cause an output equivalent to the noise output in question. This is called the noise equivalent power.

The dark current noise of our photomultiplier was equivalent to an input of 7×10^{-12} watt of light at the wavelength of the ruby laser. It could be reduced drastically by cooling the photomultiplier but this was not done because the dark current noise was not a limiting factor of performance

Spectral filtering in the telescope eliminates most illumination which originates from other sources than the laser itself. The fraction of such light incident on the photomultiplier is proportional to the bandwidth of the filter. For reasons of availability, a spectral filter with a 20-Å transmission band was used. Actually, the pass band of the filter need only be a little wider than the laser linewidth; therefore considerable improvement can be achieved by employing a narrower filter.* Filtering does not prevent laser light scattered by the atmosphere from interfering with ranging. As long as ranging is not performed by an isolated short pulse, but by an irregular sequence of pulses persisting over a few hundred microseconds, atmospheric scattering at close range may be a serious source of noise. It requires physical separation of transmitter and receiver so that the intense radiation immediately in front of the radiator does not find its way into the receiver. However, it is possible to shorten the transmitted pulse by employing a Kerr cell, or by shutting off the excitation more rapidly.

Sunlight scattered from the target, from its environment and from atmospheric particles is the limiting factor for daytime performance because of the shot noise it generates on the receiver. The field of view of the receiver is normally wide enough to admit light from objects surrounding the target. The light incident on a surface element da, from an object which radiates according to Lambert's law and which subtends a solid angle $d\Omega$ at the receiver, is

$$\frac{W_r}{\pi}\ da\ d\Omega \qquad (2)$$

where W_r is the total energy per unit surface radiated by the object under observation. Therefore if the entire field of view of the telescope is aimed at a uniform scatterer then the power received from it is $W_r A\Omega/\pi$. Thus if the scatterer reflects a fraction F of the incident sunlight the energy received in the telescope is

$$W = FW_s\ A\Omega/\pi \quad , \qquad (3)$$

where W_s is the radiation of sunlight within the spectral passband of the filter. The typical data $F = 0.2$, $W_s = 2$ watts/m^2, $A = 1.26 \times 10^{-2} m^2$, $\Omega = 5 \times 10^{-6}$ give $W = 8 \times 10^{-9}$ watt.

The relation between W the light incident on the receiver and the current I in the photomultiplier is

$$I = qe\ W/h\ f \quad , \qquad (4)$$

where h is Planck's constant and q is the quantum efficiency of the photo tube for the frequency in question. The fluctuations of I constitute the shot current, which is

$$I_N = \sqrt{2e\ I\ \Delta} \quad , \qquad (5)$$

where Δ is the electrical bandwidth of the receiver circuit. In our case $\Delta \approx 20$ mc. From these relations the equivalent incident power of the shot noise becomes

$$W_N = \sqrt{\frac{2e\ W\Delta}{q}}\ \sqrt{\frac{h\ f}{e}} \qquad (6)$$

For a quantum efficiency $q = 0.01$ we calculate from the above data $W_N = 1.2 \times 10^{-9}$ watt which is comparable to the signal power expected at 10^4 meters. Thus on a clear day in broad daylight our system is limited by shot noise caused by reflected sunlight.

One of the factors responsible for this high value of the shot noise is the low quantum efficiency of our phototube at 6943 Å. Therefore a phototube-laser combination with a higher quantum efficiency

*Optimum spectral filters are barely adequate for the ruby laser used here. As will be mentioned later, new techniques, such as optical heterodyning, will be required to match the extremely narrow linewidth generators that are in the offing.

should substantially improve performance in daylight.

At night, when the receiving telescope does not look at artificial light sources or at the moon, the shot noise is negligible. Clearly at 11,200 meters we have not reached the limit set by the dark current of the photomultiplier. The actual limits for ranging at night are probably widely variable because of variations in atmospheric scattering and because of interference of other light sources.

To sum up, significant improvements of the present system may be obtained by the following means: Higher light output and more desirable output pulse shape may be obtained by cooling and by further laser development. Higher selectivity may be had by employing a narrower spectral filter. Greater sensitivity and greater discrimination against shot noise may be had by the use of a photomultiplier tube with greater quantum efficiency at the output frequency.

Far greater improvement in optical ranging systems may be realized if advantage is taken of the light amplification possible in some lasers, or if techniques are developed which permit the mixing and heterodyning of optical signals. The technical exploitation of these phenomena has to wait until the basic processes mentioned are explored beyond their present state.

References

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3. R. J. Collins and D. F. Nelson, "Studies of the Emission from a Pulsed Ruby Optical Maser," presented at the 1961 Spring Meeting of the Optical Soc. of America.

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